

BACKGROUND OF THE INVENTION

1. Field of the Invention

This invention relates generally to the field of electrical energy conversion systems and more particularly to electrical inverter circuits utilizing a solid state active element oscillator of the multivibrator type to convert DC voltage into AC voltage.

2. Description of the Prior Art

Inverter circuits, as considered herein, are designed to convert a DC input voltage into a high frequency alternating output voltage. The push-pull types of inverter circuits are recognized as the most efficient as a class for this purpose. However, even these circuits are plagued with a number of identifiable inefficiencies. The most significant of these is the energy loss that occurs due to common-mode conduction. This occurs when both transistors conduct simultaneously. The simultaneous conduction in turn is the result of an inherent and unavoidable delay associated with the turn-off action of applicable transistors. Such transistors normally do not have a corresponding delay associated with the turn-on action. Attempts have been made to correct this problem by selecting transistors with the lowest possible turn-off delay but this approach has required the use of very costly transistors.

A second major cause of energy loss in such a circuit is the power dissipation that occurs within each transistor during its turn-off transition. To minimize this loss, it is important to operate each transistor at near its maximum switching speed.

However, it is even more important to prevent the collector voltage from rising significantly before the transistor has been fully turned off.

A third significant cause of energy dissipation results from turning on a transistor before its collector voltage has been reduced to its minimum level. This reduction of collector voltage occurs after the other transistor has been turned off, and as a result of its rising collector voltage.

Another cause of energy loss results from power dissipation within each transistor while it is conducting. To minimize this loss, it is necessary to provide adequate base drive corresponding to the collector current flowing at any given time. However, if this base drive is in excess of what is required to control the transistor, it can in itself become a cause of unnecessary power loss.

A great deal of design work on push-pull inverter circuits has been performed by others and reported in the patent art. Examples of such circuits are described in the patent to Jensen No. 2,997,664 entitled "Saturable Core Transistor Oscillator"; the patent to Wellford No. 3,248,640 entitled "Synchronizing Circuit"; the patent to Mehwald No. 3,324,411 entitled "Transistor Inverter with Inverse Feed-Back Frequency Stabilization Control"; the patent to Bishop et al, No. 3,461,405 entitled "Driven Inverter Dead-Time Circuit"; the patent to Paget, No. 3,579,026 entitled "Lamp Ballast"; the patent to Low, No. 3,663,944 entitled "Inverter Oscillator with Voltage Feed-Back"; the patent to Cox, No. 3,691,450 entitled "Power Inverter Oscillator Circuit"; the patent to Hook, No. 3,913,036

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entitled "High Power High Frequency Saturable Core Multivibrator Power Supply"; and the patent to Ghiringhelli, No. 4,016,477 entitled "Novel Multipath Leakage Transformer and Inverter Ballast". The above identified patents have recognized some of the causes of power loss within a multivibrator inverter circuit and have proposed solutions for partially correcting for these losses. However, none have recognized all of the causes of such power loss as identified herein nor have they suggested solutions for eliminating such power losses within an economical and operationally effective frame of reference. Some also employ independent oscillator or drive circuits which add to the total cost of the inverter and may be wasteful of energy in and of themselves.

Another approach to the solution of most of the identified problems has been described in my pending application entitled "High Efficiency Push-Pull Inverters", filed March 20, 1978, and assigned Serial Number 890,586. This invention employs a saturable inductor across the base-emitter junction of each transistor for providing, when saturated, a near-short circuit path for the rapid evacuation of the charge carriers stored in the junction, and thereby ensures the rapid turn-off of the respective transistor.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved self-oscillating, push-pull inverter circuit that is both efficient in operation and economical to manufacture. This invention is particularly advantageous in applications where the available DC supply voltage is higher than 50 volts as would be the case for rectified voltage from a conventional power line source.

It is another object to provide an improved push-pull inverter circuit in which energy loss due to common-mode conduction of the switching transistors is substantially eliminated.

It is still another object to provide an improved inverter circuit of this general type in which energy loss within each transistor during its turn off transition is minimized. In this regard, it is important to prevent the collector voltage from rising significantly before the transistor has been turned off completely.

It is still another object to provide an improved inverter circuit effective to minimize energy dissipation which results from turning on a transistor before its collector voltage has been reduced to its minimum level.

It is still another object to provide an improved inverter circuit in which an efficient base drive is provided to minimize power dissipation within each transistor while it is conducting. In this regard the base drive is adequate for this intended

purpose without being excessive. This prevents the base drive from becoming a source of energy dissipation in and of itself.

An inverter circuit that eliminates or substantially minimizes all of the loss factors described above is described herein wherein like characters of reference designate like parts of the several views.

BRIEF DESCRIPTION OF THE DRAWINGS

Fig. 1 is a schematic diagram of a preferred embodiment of the inverter circuit of the present invention;

Fig. 2 are characteristic wave form diagrams of the collector voltage, base voltage and collector current for both of the switching transistors of Fig. 1;

Fig. 3 is a circuit diagram of a modified inverter circuit adapted to operate at higher DC potentials;

Fig. 4 is a schematic diagram of the inverter circuit of Fig. 1 specifically adapted as a ballast for fluorescent lamps; and

Fig. 4A is a schematic diagram of a bridge rectifier adapted for use with the circuit of Fig. 4.

DESCRIPTION OF THE PREFERRED EMBODIMENTS

The improved high efficiency inverter circuit of the present invention is illustrated schematically in Fig. 1 and is designated generally by the numeral 10. The circuit 10 comprises a main transformer 11, a pair of relatively high-power switching transistors 12 and 13, a saturable current transformer 14 and a non-

saturable current transformer 15. The main transformer 11 has a primary winding 11p and a secondary winding 11s. The secondary winding 11s is connected to deliver a high frequency alternating output voltage to a pair of terminals 17 and 18. The transistor 12 has a base 12b, a collector 12c and an emitter 12e. Similarly, the transistor 13 has a base 13b, collector 13c and emitter 13e.

The inverter circuit 10 also comprises a resistor 19, a capacitor 20 and diodes 22, 23, 24, and 25. The transformer 14 has windings 26, 27 and 28 wound on a torroidal magnetic core 29. Similarly, the transformer 15 has windings 30, 31, and 32 wound on a torroidal magnetic core 33. The primary winding 11p has a center tap 34 connected to a terminal 35 which is connected to a positive source of DC voltage or B+. Similarly, the transformer 15 winding 32 has a center tap 36 connected to a negative terminal 37 or B-. The center tap 34 on the transformer 11 is connected by a lead 38 to one end of the resistor 19, and the other end of resistor 19 is connected by means of the lead 39 to the base 12b of transistor 12. The lead 39 is also connected to one end of winding 28 of transformer ~~15~~¹⁴ and to a cathode 22c of diode 22, and to an anode 24a of the diode 24. The other end of winding 28 is connected by a lead 40 to the base 13b, to a cathode 23c of diode 23 and to an anode 25a of the diode 25. The two ends of winding 32 of transformer 15 are connected to cathodes 24c and 25c. The emitter 12e of transistor 12 is connected by means of a lead 42 to an anode 22a of diode 22 and to the B- terminal 37. Similarly, the emitter 13e of transistor 13 is connected by means of a lead 43 to an anode 23a

of diode 23 and to the B- terminal 37.

One end of the primary winding 11p of transformer 11 is connected by means of a lead 44 to one end of the winding 26 of transformer 14. Similarly, the other end of the winding 11p of transformer 11 is connected by means of a lead 45 to one end of the winding 27 on the transformer 14. The other ends of the windings 26 and 27 are connected by means of leads 46 and 47 to the windings 30 and 31, respectively, of the transformer 15. The other end of winding 30 is connected by means of the lead 48 to the collector 12c of transistor 12, and the other end of winding 31 is connected by means of a lead 49 to the collector 13c of transistor 13. The capacitor 20 is connected between the leads 48 and 49.

The operation of the inverter circuit of Fig. 1 may be described in conjunction with the wave form diagrams of Fig. 2. A positive starting bias signal is provided from B+ through resistor 19 and lead 39 and through winding 28 and lead 40 to the bases 12b and 13b, respectively. This bias current is effective to trigger one or the other of the transistors 12 or 13 into conduction. Assume that transistor 12 is the conducting transistor at the time t_1 ; the base voltage E_b has been driven to a positive state, and the collector current I_c rises. The collector voltage E_c is substantially zero or only slightly positive while the transistor 12 is conducting. Current from B+ flows through the main transformer winding 11p and lead 44 through winding 26 of transformer 14, through winding 30 of transformer 15, and through lead 48, collector 12c, emitter 12e and lead 42 to B-. The current flowing through winding 26 produces a changing flux in the core 29 of transformer 14. So long as this core 29 is not saturated, the winding 28 provides a positive feed-back to the base 12b. The current path from

B- one end of the winding 28 is through lead 39, base 12b, emitter 12e, and lead 42 to B-. A return current path to winding 28 is provided from B- through lead 43, diode 23 and lead 40 to the other end of winding 28.

At some time t_2 core 29 becomes saturated and positive feed-back to the base 12b ceases. The winding 28 in effect becomes a short circuit between the bases 12b and 13b. Until the core 29 saturates, the transformer 14 provides the dominant feed-back to the base drive circuit. However, when the transformer core 29 does saturate, the transformer 15 then provides the dominant feedback control. The transformer 15 is designed so that the core 33 is not saturated by the same conditions that cause the transformer 14 to saturate. The winding 32 of transformer 15 provides a *or negative* subtractive feedback through the diode 24 to the base 12b. The implication of this performance is that as soon as the transformer 14 saturates the base drive current reverses, thereby rapidly evacuating the stored charge carriers from the base emitter junction of transistor 12. As soon as the base emitter junction of transistor 12 is evacuated of carriers, the current taken by winding 32 of transformer 15 starts flowing through the diodes 22 and 24 and center tap 36 to B-.

It should be noted that the subtractive feedback which causes the rapid evacuation of the charge carriers from the base emitter junction of transistor 12 prevents any positive voltage transients on the base 13b of the opposite transistor 13. The saturated core 29 of transformer 14 in effect provides a short circuit through the winding 28 between the bases 12b and 13b so that both remain negative.

Due to the unidirectionally subtractive current from transformer 15, both base voltages will stay at a negative voltage for as long as current flows through winding 32 of transformer 15, which is for as long as collector current I_C continues to flow. The implication of this is that it does not matter that the transistors 12 and 13 may have significant turn-off delays. The non-conducting transistor simply cannot be turned on until current has stopped flowing through the opposite transistor.

The capacitor 20 connected between the collectors 12c and 13c serves to restrain the rate of rise until time t_4 of the collector voltage E_C after the conducting transistor 12 is turned off. As a result, the transistor 12 is turned off completely before its collector voltage rises to any significant level. This greatly minimizes power dissipation in the transistor during the turn-off transition. It should be noted that the capacitor 20 also bridges the windings 30 and 31 of the transformer 15 and provides a path for continuity of current flow through the current feedback transformers 14 and 15.

The main transformer 11 contains some amount of leakage inductance. This inductance in effect provides inertia to the current flow so that the collector voltage E_C on the transistor 12 that is being turned off could rise to a very high level. However, the ultimate voltage that can be reached by the collector of the off-transistor cannot be more than twice the magnitude of $B+$. From the nature of the circuit, it may be noted that when the collector voltage E_C of one transistor has risen to a magnitude of twice $B+$, the voltage on the collector of the other transistor has fallen to zero. Also, the collector

voltage cannot rise beyond twice the magnitude of B+ because the other transistor 13, in combination with its base to emitter diode, acts as a clamp.

In order to eliminate the turn-on losses entirely, the off-transistor should not be turned on until after its collector voltage has reached zero. This is precisely what is accomplished by the base drive circuits in the operation of the transformers 14 and 15.

A The operation of transistor 13 can be described by reference to the lower or second set of wave form diagrams of Fig. 2, which are substantially identical to the upper set shown for transistor 12 -- only displaced in time. Between time t_4 and t_5 the collector voltage E_C of transistor 13 decreases to slightly below zero. The rate of decline corresponds to the rate of rise of the collector voltage of the now "off" transistor 12. This rate of change is restrained by the charging of the capacitor 20, and continues until clamping takes place. At time t_4 , a negative current I_C begins to flow between the base 13b and collector 13c and continues until time t_5 . The path for this current flow is from B- through diode 23, the base-collector junction of transistor 13, windings 31 and 27, and winding 11p of transformer 11 to B+. This results in a return of energy to the power supply, during this time span. The transistor 13 and diode 23 in this mode function as a clamp to limit the magnitude of the voltage of the collector 12c of transistor 12.

At time t_5 , the base 13b is driven positive and transistor 13 begins to conduct in a positive direction. The path for this

current flow I_C is from B+ through the right half of winding 11p, through windings 27 and 31, collector 13c, and emitter 13e to B-. A positive feedback is provided from winding 28 of transformer 14 to the base 13b. The current I_C continues to flow until time t_7 , shortly after the transformer 14 saturates, at time t_6 , and positive feedback to the base 13b ceases. At this time, the transformer 15 takes over and supplies a subtractive feedback to the base 13b rapidly evacuating its charge carriers. The transistor 13 is turned off and its collector voltage begins to rise until time t_8 , completing the cycle of operation.

The alternate conduction of each transistor 12 and 13 produces current flow through winding 11p of transformer 11 in opposite directions. This alternating current in winding 11p is transformed into a high-frequency AC voltage at the secondary winding 11s which is supplied to the output terminals 17 and 18.

Referring now to Fig. 3, the circuit therein illustrated is capable of operating at higher DC potentials for a given voltage limit on the transistors than is the circuit of Fig. 1, although the principles of switching control are substantially the same. The inverter circuit of Fig. 3 is designated generally by the numeral 110 and comprises the main transformer 111, switching transistors 112 and 113, a non-saturable current transformer 114 and a saturable current transformer 115. The circuit 110 also includes a pair of capacitors 116 and 117 connected in series between a B+ terminal 118 and a B- terminal 119. The circuit 110 also includes a capacitor 120, a resistor 121 (or other bias means) and diodes 122 and 123, 124, 125, 126 and 127. The transformer 114 has windings 130, 131, and 132 wound on a toroidal core

133. Transformer 115 has windings 134, 135, and 136 wound on a toroidal core 137. The collector of transistor 112 is connected by means of a lead 140 to the B+ terminal 118. The emitter of transistor 112 is connected to the collector of transistor 113 by a lead 141. The emitter of transistor 113 is connected to a lead 142 which is connected to the B- terminal 119. The transistors 112 and 113 are effectively connected in series between the B+ and B- terminals and their operation is controlled by the base drive circuit which includes the transformers 114 and 115 so as to deliver a high frequency alternating voltage output to the secondary 111s of transformer 111. The transistors 112 and 113 in this embodiment must be capable of withstanding a DC voltage equal to B+ whereas transistors 12 and 13 of Fig. 1 must be capable of withstanding twice B+.

One end of the primary winding 111p of transformer 111 is connected to a junction 145 between the capacitors 116 and 117. The same end of winding 111p is connected to one end of the resistor 121. The other end of resistor 121 is connected by a lead 146 to the anode of diode 125 and to one end of winding 132 on the transformer 114. The other end of winding 132 is connected to a lead 147 which in turn is connected to one end of the winding 136 on the transformer 115 and to the cathode of diode 127. The other end of winding 136 is connected by means of lead 148 to the cathode of diode 123 and to the base of transistor 113.

The other end of winding 111p of transformer 111 is connected by means of a lead 150 to one end of the winding 131

on transformer 114. The other end of winding 131 is connected by a lead 151 to one end of winding 135 on the transformer 115. The other end of winding 135 is connected to lead 141. The lead 141 is connected to the emitter of transistor 112, the collector of transistor 113, the cathode of diode 124, the anode of diode 122, and the anode of diode 126 and to one side of the capacitor 120. The other side of the capacitor 120 is connected to the B- lead 142. One end of the winding 130 of transformer 114 is connected by a lead 155 to the base of transistor 112, to the cathode of ~~transistor~~ ^{diode} 122, and to one end of winding 134 of the transformer 115. The other end of winding 130 is connected to the anode of diode 124. The other end of winding 134 of transformer 115 is connected to the cathode of diode 126.

In operation, the circuit of Fig. 3 functions as follows: The total DC potential between the terminals 118 and 119 is applied across the capacitors 116 and 117, the junction 145 generally being at one-half of the total DC potential; although it is to be understood that the series connection of capacitors 116 and 117 could be a voltage divider of some comparable type. The capacitors 116 and 117 block the passage of DC but readily permit the passage of alternating current. A DC bias is applied from junction 145 through the resistor 121, lead 146, winding 132, lead 147, winding 136, and lead 148 to the base of transistor 113. The transistor 113 is triggered into conduction and current flows from the junction 145 through the primary winding 111p, lead 150, winding 131, lead 151, winding 135, and lead 141 to the collector of transistor 113, and through the emitter of transistor 113 to B-. A return path is provided

through the capacitor 117 to the junction 145. The current flowing through winding 135, together with the effect reflected by winding 136, magnetizes the core 137 in one direction. Until this core 137 is saturated, the transformer 115 provides a dominant positive feedback through winding 136 to the base of transistor 113 to maintain this transistor in a state of conduction. At some point in time, the core 137 of transformer 115 saturates and positive feedback to the base of transistor 113 ceases. At this point, the output of winding 132 of transformer 114 becomes the dominant control and delivers a subtractive feedback for the rapid evacuation of charge carriers from the base of transistor 113. The path for this current being through the windings 136 and 132, diode 125 and partially through diode 127 to B- until the charge carriers are evacuated. Thereafter, the return path is totally through diode 127. The principal function of the transformer winding 132 therefore is to maintain the voltage on the cathode of this diode 127 negative throughout both feedback cycles. The transformer 115 also provides a positive feedback from winding 134 to the base of transistor 112 to trigger this transistor into conduction. In this latter case, current now flows from B+ through lead 140, the collector of transistor 112 and the emitter of 112 to the lead 141, and through the windings 135 and 131, and primary winding 111p to the junction 145. The return path to B+ is provided from the junction 145 through the capacitor 116. The direction of current flow through the windings 131 and 111p during this half cycle is in the opposite direction from that first described when transistor 113 was conducting so that an alternating voltage output is provided at the secondary 111s of the transformer 111. The winding 13⁴₆ of

transformer 115 continues to provide a positive feedback to the base of the transistor 112 to maintain it in conduction. When core 137 becomes saturated, this feedback ceases. Transformer 114 which is not saturated now provides a subtractive feedback to force evacuation of charge carriers from the base of transistor 112 through winding 130 and diode 124 to the emitter connection 141. When the transistor 112 is cut off, the transistor 113 is triggered into conduction by a signal from winding 136 as previously described.

The circuit 110 thus provides an effective means for controlling the conduction of transistors 112 and 113 to provide a high frequency AC voltage output at the secondary 111s of transformer 111. The sequential operation of the saturable transformer 115 and non-saturable transformer 114 ensures that the non-conducting transistor 112 or 113 is not switched on until the conducting transistor is switched completely off. The capacitor 120 connected across the collector and emitter junction of transistor 113 restrains the rate of rise in voltage at the collector of transistor 113 during these transient stages.

When transistor 113 is turned off, the voltage at its collector begins to rise due to the current flowing from the junction 145 through transformer winding 111p and through winding 135. Further due to the inertia effect of the leakage inductance of transformer 111, the collector voltage continues to rise until it is clamped. A current path is then established from the collector of 113 through diode 122 and the base-collector junction of transistor 112 to B+. This negative current continues to flow until the energy stored in the leakage inductance of transformer 111 is discharged and returned to the power supply. This current also conditions the transistor 112 so that for a brief period it can conduct in the positive direction.

The circuit of Fig. 1 can utilize inexpensive and readily available transistors and with such transistors can operate at B+ voltages as high as 300 volts. In the circuit of Fig. 3 DC voltages as high as 600 volts can be accommodated. This would correspond to root mean square voltages from the power line as high as 420 volts, if the power line voltage is directly rectified and used as a B+ supply.

Referring now to Fig. 4, there is illustrated a circuit diagram of an inverter circuit similar to that of Fig. 1 but specifically adapted for use as a ballast for two 40 watt fluorescent lamps 201 and 202. The circuit as a whole is designated by the numeral 210 and comprises a transformer 211, having a primary winding 211p. Secondary windings 203, 204 and 205 are provided for the filaments of the lamps 201 and 202. A current limiting inductor 206 is connected in series with the lamps 201 and 202 across the primary winding 211p.

The circuit 210 also comprises switching transistors 212 and 213, a saturable transformer 214, a non-saturable transformer 215, a resistor 219 and capacitor 220. The circuit 210 also contains diodes 222, 223, 224, and 225. The transformer 214 has windings 226, 227 and 228 on a toroidal magnetic core 229. Similarly, the transformer 215 has windings 230, 231 and 232 on a toroidal magnetic core 233. A center tap 235 of the primary winding 211p of the main transformer 211 is connected to a B+ terminal; and a center tap 237 of the winding 232 of transformer 215 is connected to a B- terminal.

A rectified DC voltage supply may be provided from a conventional AC source as shown in Fig. 4A. A pair of AC terminals

250 and 251 may be connected to a conventional 120 volt 60 hertz source across a bridge network 252. The bridge network 252 comprises 4 diodes 253, 254, 255, and 256 connected as shown. An electrolytic capacitor 257 can be connected across the output of the bridge network 252 to provide a filtered DC voltage to the B+ and B- terminals. The components utilized in the circuit 210 may be of the types and values as indicated in the accompanying table.

TABLE I

Lamps 201 and 202	40 w R.S. Fluorescent
Inductor 206	F41814 Cup Core
Transformer 211	F42213 Cup Cores
Transistors 212 and 213	FT49
Resistor 219	67 K Ω
Capacitor 220	1200 pf.
Diodes 222-225	1N 4001
Core 229	W40401 TC
Core 233	W40402 TC

The complete embodiment of the ballast circuit of Fig. 4, utilizing the components as indicated results in an efficient device that is small, light-weight, and compact. The ballast circuit constructed as indicated may have one-tenth or less of the total weight of a conventional ballast and may occupy a volume of one-sixth or less of that of the conventional ballast circuit. The circuit 210 functions in substantially the same manner as the inverter circuit described in Fig. 1 except that a relatively high frequency AC voltage is developed directly across the primary winding on the main transformer rather than across a secondary winding.

The circuits of the preferred embodiments have been described herein as utilizing NPN switching transistors. It is to be understood that the principles involved are equally applicable to comparable circuits utilizing PNP transistors.

It is to be understood that the embodiments shown and described are by way of example only and that many changes may be made thereto without departing from the spirit of the invention. The invention is not to be considered as limited to the embodiments shown and described except insofar as the claims may be so limited.

Glossary of Terminology

1. Leakage inductance, as defined herein, shall mean an effective shunt or parallel inductance as typically obtained by providing an air gap in the magnetic path of the transformer.

2. The collector-emitter saturation voltage is a condition where there is adequate base current to correspond to the collector current so that additional base current will not substantially decrease the collector-emitter voltage. The collector voltage, as described herein, is referenced to the emitter.